Next Generation Internet Bandwidth Markets

William Lehr
Graduate School of Business, Columbia University and MIT Internet Telephony Consortium

email: wlehr@rpcp.mit.edu

Lee McKnight
Fletcher School of Law and Diplomacy, Tufts University and MIT Internet Telephony Consortium

email: lmcknigh@tufts.edu

Prepared for submission to:

Communications & Strategies
Special Issue on Internet Economics
(Forthcoming)

&

IDATE Conference
Montpellier, France

November 18-19, 1998

I. What Is a Bandwidth Market?[1]

Bandwidth markets are already operating worldwide in a number of forms. Nonetheless, these markets are still quite primitive when compared to financial markets or the commodity markets for agricultural or energy products. If bandwidth markets are to play a similarly sophisticated role for the Internet community, then they need to develop and mature. This article focuses on the role of these markets in the Internet, the forces and challenges confronting their development, and the research that is needed to understand the economic, technical and policy mechanisms that will underlie the development these markets.

Bandwidth markets are wholesale markets for telecommunications services, including both voice and data communications services, and particularly, including IP services. We are especially interested in the emergence of spot markets for commoditized IP bandwidth, and in the emergence of derivative futures and options markets that might be used to more efficiently distribute the risk of investments in facilities infrastructure and complementary assets (*e.g.*, in brand image, product awareness, or other retail-level assets that may be predicated on the future availability of low cost transmission capacity). Efficient spot markets that would allow buyers and sellers to exchange IP transport capacity on short notice, in response to real or near-real-time market conditions are needed to support robust competition among multiple facilities-based and non-facilities-based carriers.

Wholesale markets for telecommunications services already exist in the form of interconnection agreements and various forms of capacity arbitrage. For example, switched resale of capacity purchased according to volume and term commitment discounts plays an important role in assuring the competitiveness of domestic long distance services in the United States. The exchange of Internet traffic at public network access points (NAPs) provides an example of another form of wholesale market. The future role of these public NAPs where carriers of unequal size interconnect to exchange traffic without termination charges (*i.e.*, subject to a "bill and keep" arrangement) is currently suspect.

The exhilarating growth rates of Internet traffic and transmission capacity enabled by advancing technologies such as Wave Division Multiplexing and the massive worldwide investment in terrestrial, undersea, wireless, and satellite capacity is fueling the need for IP bandwidth markets. With exponential growth ongoing, the question of how to cope should growth subside or cease ought to be a significant concern to facilities planners and investors. Bandwidth markets and derivative markets for futures or options on infrastructure capacity could play an important role in managing the risk of these

[1] This paper draws upon research supported by the Massachusetts Institute of Technology's Internet Telephony Consortium (http://itel.mit.edu). We acknowledge the contributions of our industry and academic colleagues within the ITC to this work. The views expressed, however, are those of the authors, and are not necessarily shared by MIT, the ITC, its sponsors, or Tufts University. Any errors of fact or by omission are the author's sole responsibility.

facilities investments. However, these markets may also contribute to market instability if they fail to function properly. Therefore, a more thorough understanding of bandwidth markets is important to the future evolution of the Internet.

The balance of this article is organized into four sections. In Section II, we explain why bandwidth markets are critical for the evolution of the Internet. In Section III, we discuss precursors and the likely development path for the emergence of more complete IP bandwidth markets. Section IV examines the roadblocks that must be overcome for these markets to develop. And, Section V identifies areas where future research is required.

II. The Internet and the Need for Bandwidth Markets

In this section, we consider why the Internet and IP technology help facilitate the emergence of bandwidth markets. The reasons include the impact of the Internet on the structure of communications industries, on the growth and uncertainty of traffic demand, and on the architecture of networks. Each of these issues will be addressed in turn.

The Internet is helping to drive convergence, leading to the elimination of traditional industry boundaries separating broadcast television, computers, telecommunications, and data services. As Kavassalis and Lehr (1998a,b)[2] explain in greater detail, IP technology is unique in its ability to provide a *spanning layer* that supports the flexible integration of multiple applications (data, voice, or video) on a variety of underlying facilities-based infrastructures (ethernet, leased lines, ATM, frame relay, etc.). Briefly, the IP protocol provides an *application-blind* interface to the facilities-provider and a *technology-independent* interface to the service provider, thereby permitting the decoupling, or vertical-disintegration of communication service providers. While in the past, network services were offered on single purpose networks by vertically-integrated carriers (*e.g.,* television via over-the-air or CATV broadcast networks; telephone services over the PSTN; etc.); today and in the future, IP permits owners of the underlying facility infrastructure to support multiple applications, or alternatively, to allow service providers to utilize multiple infrastructure technologies. This flexibility creates opportunities for new types of firms to emerge that are not vertically integrated (*e.g.,* the carriers' carrier or the non-facilities-based value-added service retailer). This encourages competition and innovation at all stages within the communications infrastructure value-chain.

For the full potential of the Internet and IP technology to be realized, however, it is obvious that there must be robust wholesale markets for the underlying transport services. That is, the Internet requires the emergence of bandwidth markets for its continued evolution into an ubiquitous global information infrastructure. The viability of non-integrated strategies presumes the existence of markets for buying and selling wholesale transport services of the sort discussed in the preceding sections.

[2] See Petros Kavassalis and William Lehr [1998a], "Forces for Integration and Disintegration in the Internet," Communications and Strategies, Number 30, 2nd Quarter 1998, 135-154; and, Petros Kavassalis and William Lehr [1998b], "The Flexible Specialization Path of the Internet," paper presented to *Beyond Convergence - International Telecommunications Society Conference*, Stockholm, Sweden, June 1998. See also *Realizing the Information Future: the Internet and Beyond*, National Research Council, Washington, DC: National Academy Press, 1994.

Even in the absence of non-integrated strategies, however, industry convergence and the dramatic growth in the range and volume of traffic associated with the Internet contributes to the emergence of bandwidth markets. First, meeting this demand growth requires a huge expansion in capacity. Because of scale economies, it is common to install capacity in substantial increments that result in localized (and often, market-wide)[3] surplus, at least in the short-run. The owners of this surplus capacity have an incentive to lease it to other carriers until it is needed to satisfy the owner's own needs. Of course, if the facilities-based provider has significant market power, as it may choose not to lease the available surplus capacity to potential competitors. With competition, however, the ability of a single carrier to discipline the market by withholding capacity is reduced. The Internet encourages competition.

Second, IP technology may offer a lower cost path to building a facilities network. This is because of IP's modularity; its reliance on open standards which encourage competition and facilitates the adoption of cost-saving innovations; and, the focus on end-user control, that reduces the switching costs associated with network or service modifications. The reduced costs of building networks and market-opening, liberalized regulatory policies encourage increased entry by facilities-based carriers. This further contributes to the availability of localized surplus capacity that is a necessary prerequisite for bandwidth markets to emerge. Similarly, the increased entry also provides a ready source of demand for surplus bandwidth. Even carriers that intend eventually to be fully-facilities-based cannot construct their networks overnight and need to lease capacity from other carriers in the interim.[4]

Third, the Internet increased demand uncertainty in both a dynamic and static sense. The increased demand uncertainty increases the difficulty of network provisioning and facilities planning. Bandwidth markets reduce the costs of adjusting available capacity to meet realized demand. The rapid growth in traffic and the proliferation of new services fueled by the Internet has increased dynamic market demand uncertainty. When growth is exponential, even a small change in forecasted growth rates can have a dramatic impact on projected market size. Moreover, the increased competition means that firm demand uncertainty is larger still. Industry convergence means that capacity can be shared across multiple applications. That is, we do not have to know *ex ante* what tomorrow's killer app will be, we only need know that one will exist to justify investing in capacity today.

The Internet increases demand uncertainty in a static sense as well. Data traffic is inherently less predictable than voice traffic leading to an increase in traffic burstiness

[3] Even if capacity is constrained in the overall market, there are likely to be localized sources of surplus capacity. Moreover, in a network of networks, the stochastic nature of demand will lead some carriers to have surplus capacity while other carriers will be constrained. This creates the potential for a bandwidth market.

[4] The network unbundling provisions in the United States' Telecommunications Act of 1996 were adopted, in part, to facilitate efficient entry into local telephone services. The Act recognized that new entrants would need to lease facilities from the incumbent while building out their networks.

(*i.e.,* peak to average bandwidth required)[5]. Accommodating this bursty traffic helps drive the need for spot markets in bandwidth to allow carriers to share the costs of provisioning for peak traffic. This is also closely related to the need for surplus provisioning to meet requirements for increased network reliability. As the Internet carries an ever-larger share of mission critical services it will have to provide reliability comparable to what we are used to from the PSTN. Capacity sharing agreements that may help provide the underpinnings for bandwidth markets are important in order to meet these reliability needs at an affordable cost.

Fourth, the Internet's underlying architecture helps drive the need for bandwidth markets. The packet-switched Internet offers a much larger range of routing options than a traditional circuit-switched telephone network. This allows network facilities to serve as effective substitutes over a much wider geographic range. This effect is stronger for the delay insensitive traffic that comprises the bulk of Internet traffic today (*e.g.,* Web browsing as opposed to Internet Telephony). Allowing more facilities to serve as substitutes with respect to traffic between two end-nodes increased the depth or liquidity of potential bandwidth markets.

III. Antecedents and Requirements

Wholesale markets have been operating for more than a century, as in, for example, the international telephony traffic revenue sharing arrangements which have long been brokered through the International Telecommunication Union, and settled in gold francs.

In the past (and currently) carriers have agreed to exchange traffic and bandwidth on demand. Now, primitive exchanges have sprung up to facilitate the matching of supply and demand, for service providers (resellers) and/or facilities-based carriers. In the future, we expect exchanges or markets to facilitate trading, hedging, and speculating in bandwidth by carriers, resellers/service providers, users, and bandwidth speculators.

These markets are likely to evolve from existing markets for bulk transport services and to include new types of markets for other essential services. The types of commodities which may be traded in the new bandwidth markets include:

- Leased lines
- Frame relay circuits
- Transponder spot markets
- Switched and terminated minutes
- Billing bandwidth and accounting services
- ITXC, Band-X, RateXchange, Arbinet, and other emerging markets to exchange transport capacity.

After these primary markets for bandwidth and associated services grow to sufficient scale, secondary markets may also emerge in bandwidth options, futures, and

[5] See Frank Kelly [1997], "Charging and Accounting for Bursty Connections," pages 253-278 in *Internet Economics*, edited by Lee McKnight and Joseph Bailey, Cambridge, MA: MIT Press, 1997.

derivatives.[6] Futures and options markets can be used by multinational firms to hedge the risks of uncertain bandwidth demand and capacity. With Internet bandwidth requirements growing so rapidly, the probability of accurately forecasting demand is low while the costs of forecast errors are growing as networks become increasingly "mission critical." These forces favor the emergence of derivative markets for capacity.

The Internet has supported a literally "free" market in bits since its inception. The peer-to-peer architecture of the Internet is predicated on the expectation that receivers of bits should send or forward the bits to their destination.[7] Today, Internet interconnection takes place in a variety of market and non-market settings. Traditionally, peer-to-peer Internet interconnection occurred without settlements or fees of any kind (*i.e.*, each network was responsible for only its costs). Costs were partially or fully subsidized by the National Science Foundation, and prior to that, by DARPA. With the commercialization of the Internet, a variety of Internet interconnection – or – exchange – arrangements emerged.[8] These range from the peer-to-peer (no settlements/no cost) exchanges by the largest backbone providers to hierarchical exchanges at prices set by supply and demand between ISPs of varying sizes and skills to cooperative and administrative exchanges through cooperative facilities such as the Network Access Points of Metropolitan Area Ethernets (MAE's).

Alternative models for supporting wholesale markets for IP services might include short-term "spot" purchases and sales of bandwidth, switched transport, interconnect minutes, transponder time, transponder bandwidth, as well as the purchase and sale of long-term capacity such as leased lines, bulk transport, IRU/MIUs, transponders, "forward" contracts, and interconnect capacity at POPs. The offers might come to include derivatives and other products. As with real estate investment trusts, we might imagine the emergence of markets for securitized bandwidth capacity. Markets are also emerging to perform a variety of support functions, such as directory services, billing, international interconnection, settlements, and other functions. The table below, derived from Tyler and Joy (1997)[9], provides an analytic framework for categorizing bandwidth markets.

---

[6] In addition to examining the characteristics of the above markets for telecommunications services, it is worthwhile analyzing markets for electric power wheeling arrangements, intermodal freight transport, and Airline ticket resale markets for the lessons and insights they may offer to the developers of bandwidth markets.

[7] See David Clark [1988], "The Design Philosophy of the DARPA Internet Protocols," *Computer Communication Review*, 18 (4): 106-114.

[8] See Joseph Bailey, Husham Sharifi, and Lee McKnight [1998], "Critical Business Decisions for Integrated Services," paper presented at the *1998 Information Resources Management Association International Conference*, Boston, MA, May 1998; Joseph Bailey [1997], "The Economics of Internet Interconnection Agreements," pages 155-168 pages 253-278 in *Internet Economics*, edited by Lee McKnight and Joseph Bailey, Cambridge, MA: MIT Press, 1997; or Padmanabhan Srinagesh [1997], "Internet Cost Structures and Interconnection Agreements," pages 121-154 pages 253-278 in *Internet Economics*, edited by Lee McKnight and Joseph Bailey, Cambridge, MA: MIT Press, 1997.

[9] See Tyler, Michael and Carol Joy, 1.1.98, Telecommunications in the New Era: Competing in the Single Market, London: Multiplex Press, 1997. The Table is from Chapter 22, "The Merchant Operator", pages 194-204.

	Long-term	Short-term
Buy	Capacity • Leased Lines • Wholesale (IRU/MIU), satellite transponders, and forward contracts • Interconnect capacity at POPs	Spot purchases • Bandwidth • Switched transport Interconnect minutes
Sell	• Bulk transport of minutes (take or pay) to large users or other carriers	Spot sales of excess bandwidth Switched minutes to end-users or other carriers

Tyler and Joy comment "The emergence of 'spot' and 'forward' markets, and of forms of contract such as 'take or pay' that are familiar in other industries but novel in telecommunications, will be significant milestones on the road towards normality: that is, towards the telecoms service marketplace becoming more like other markets for products like gas, petroleum, or grain."[10]

We expect markets for long haul IP services to emerge first for the same reasons that wholesale markets for transport services and resale are more robust and developed in long distance telephone services than in local telephone services. In the former, capacity is much less geographically-specialized than in local services (*i.e.,* local facilities are really local -- to compete for a customers residential access services, multiple facilities need to pass the customer's home). Because of the specificity of local facility investments, it is not clear that local bandwidth markets will emerge. However, there may be an opportunity for bandwidth markets to emerge at points where local traffic is aggregated for interconnection to the wider-area transport infrastructure (*e.g.*, at points of interconnection to community portals/networks or shared tenant services).

At a minimum, for these bandwidth markets to be successful, they must permit capacity to be shared across multiple, independently owned network domains -- to wit, a network of networks. Moreover, the capacity must be reallocable across multiple buyer/seller pairs. Economically, the goal of these markets is to facilitate competition between a changing set of facilities and non-facilities-based carriers. Efficient spot markets for bandwidth ought to allow non-facilities-based carriers to obtain requisite transport

[10] *Ibid*., page 197.

services at a cost that is not much higher than the forward-looking cost incurred by facilities-based carriers. These are necessary to allow non-integrated firms to compete with integrated carriers on an equal footing.

IV. Roadblocks on the Path to Bandwidth Markets

The emergence of IP bandwidth markets will require new technology, new institutions, new market structures, and potentially, new regulatory policies. In this section, we consider some of the hurdles and road blocks that must be overcome as these markets continue to evolve and develop.

As noted above, the term bandwidth markets encompasses a wide range of actual and potential inter-related markets. Further refinement of the core IP services that will be traded will be necessary if effective spot or near-spot markets are to develop. This will require the adoption by industry participants of common interconnection standards, protocols, and terms of trade. Buyers and sellers will have to agree on a limited set of contract types, each of which is associated with a well-defined and generally understood set of IP services. Just as there is a limited menu of private leased line options (*e.g.*, 56 Kbps, E1, or DS-3; ATM, Frame Relay, or clear channel; etc.), we should expect to see a limited set of wholesale IP services actually traded. It is perhaps best to allow these industry "standards" to develop as *de facto* standards following experimentation in the market. These may evolve from the current markets for bulk bandwidth represented by the markets for leased lines, satellite transponders, and IRUs discussed earlier to a menu of IP transport services ranging from simple bare-bones IP interconnection to quality-of-service differentiated, end-to-end IP transport, including arrangements for authentication, billing, and settlements.

Further technical developments are needed to facilitate the smooth interconnection of networks to allow carriers and service providers to smoothly trade IP bandwidth services. This includes both enhancements to the basic IP protocols to enable reliable end-to-end delivery of quality-differentiated services (*e.g.,* as reflected in the efforts of the IETF's DiffServ and IntServ standards development efforts) as well as the development of automated trading mechanisms. Such automated trading mechanisms will be needed to enable near real-time spot markets to emerge (*i.e.,* exchanges of bandwidth that are negotiated and completed within a short period of time -- perhaps hours or minutes, although not necessarily within the transit time of an individual packet). These mechanisms will have to allow buyers and sellers to be matched, to negotiate their transaction securely and reliably, and to mediate the actual exchange of bandwidth for money to consummate the transaction. To minimize transaction costs, these mechanisms need to function without a lot of overhead in terms of either network resources or oversight supervision. Academics and industry researchers and entrepreneurs are currently exploring the theoretical and practical implications of alternative models.

In addition to the requisite automated trading mechanisms, bandwidth markets will require further developments in dynamic routing and security. Dynamic routing is needed to allow networks to take advantage of alternative sources of bandwidth in near-real time based on changes in the price of using alternative routes. This capability needs to be built into the network infrastructure at least at the level of granularity at which bandwidth markets will operate (*e.g.*, a buyer must be able to take advantage of bandwidth made available from multiple suppliers at a bandwidth exchange node). Improved security will be needed to assure both buyers and sellers that participation in these spot markets will not compromise the integrity of carriers' networks or end-to-end services. The desire to guarantee secure control over one's network provides a principle driver for self-provisioning networks. To compete with this alternative, spot bandwidth markets must be able to offer comparable security and reliability guarantees.

In addition to new technology, bandwidth markets will require new institutions and market structures. There needs to be an actual market where buyers and sellers may meet to negotiate bandwidth transactions. This market may be either localized or distributed. Obviously, the interexchange of actual bandwidth must take place somewhere, but this could either be between buyer/seller POPs or at a super Network Access Point (NAP) where multiple suppliers and buyers interconnect to exchange traffic. If the former, then the market may serve solely to facilitate the matching of buyers and sellers and to attend to the administrate details of the transaction. In the latter case, the exchange NAP plays a critical role traffic exchange. In both cases, buyers and sellers need not meet face-to-face as in commodity or stock exchanges of old, but rather are expected to meet electronically. Both localized and distributed models of exchange are evolving and may operate together. For example, Band-X, one of the first of the new bandwidth exchanges, began as a forum for matching buyers and sellers and is moving into the role of a physical exchange, as well, with the addition of its own switch.[11]

There may be one or multiple markets. Different markets may co-exist (as in NASDAQ and the New York Stock Exchange) to sell different IP services (*e.g.*, raw bandwidth between specific locations). However, to assure adequate liquidity, there are likely to be increasing returns to scale to consolidating market activity in a limited number of exchanges. As noted earlier, efficient markets require minimal transaction costs. This, in turn, requires that there be sufficient liquidity to sustain the market. There must be an adequate number of both buyers and sellers to assure effective competition and a narrow spread in bid/ask spreads.

If there are multiple markets selling similar or differentiated goods, then mechanisms will be required to coordinate activity across the different markets. If there is only one market, then it has the potential to become a bottleneck which may require regulatory oversight.[12]

The markets may be either public or private. Currently, backbone Internet service providers exchange most of their traffic via privately negotiated bilateral interconnection

[11] See http://www.band-x.com for further information. Band-X operates a switch in the switching hub, Telehouse, in London.

[12] Industry self-regulation may offer a viable substitute to government regulation if the market is adequately competitive. Some level of government oversight is nonetheless likely to be required, just as the U.S. Securities Exchange Commission provides oversight and sets financial standards for the self-regulation of the New York Stock Exchange , NASDAQ, and other financial markets.

agreements. These have superseded the exchange of traffic at public interexchange points in many cases. Even traffic exchanged at so-called "public" interexchange points may have restrictions imposed on who may participate or interconnect. These restrictions may be necessary and sensible, as in requirements that interconnection occur at a specified bandwidth (*e.g.*, OC-3 or higher); however, they also pose the potential for anticompetitive restrictions to perpetuate or extend the market power of a limited subset of carriers. Setting policies for access to the markets and fees for transactions will become important as these markets mature and consolidate.

On the administrative-side, a bandwidth exchange can serve a number of important functions beyond providing a mechanism for matching buyers and sellers. The exchange can encourage buyer/seller confidence by certifying buyers and sellers and by helping to insure against delivery risk. This can occur either when bandwidth that is used is not paid for or when bandwidth that is paid for is not delivered. The potential for the latter is especially relevant in the case of forward contracts and likely to be important in markets with lots of new entrants, many of which may have limited track records (*i.e.,* is future bandwidth purchased from an AT&T as likely to be delivered as bandwidth purchased from Level 3 or an even newer purveyor of capacity?).

The exchange may also operate as a source of liquidity to help stabilize prices by maintaining a form of "market makers" that step in to help offset temporary supply or demand shortfalls. The potential for such a role is at this time speculative, but indicative of the sorts of institutional changes that may be required for robust wholesale spot markets to develop.

Bandwidth markets will require a pricing mechanism. This will include both the mechanism by which individual buyers and sellers negotiate a price (*e.g.*, the price offer/bidding mechanism adopted) as well as the mechanism for aggregating or communicating pricing behavior to the rest of the market. For example, for a viable secondary market or derivatives markets to emerge (*e.g.*, financial options on bandwidth pricing), it will be useful to have market indices like the Dow Jones or S&P indices to track changes in the relative level of prices. Both Band-X and RateXchange publish versions of such indices.[13] Once established, such indices can be used in contracts to specify the terms and enable more flexible ways to manage and apportion the risks of market exchanges.

Finally, as these markets develop and become more important, regulatory oversight may be needed to assure that the rules of exchanges are enforced and to monitor the performance of the market. For the markets to be useful, they need to offer a viable way to manage risk which means that the variance in prices ought to be predictable and smaller is better.

The preceding discussion highlights only a small subset of the changes that are needed for the full realization of viable IP bandwidth markets. The emergence of these markets

[13] See http://www.band-x.com or http://ratexchange.com for samples of these.

will perforce need to be evolutionary, not revolutionary -- although their emergence represents a revolution in industry structure. We are entering a phase of market experimentation, during which a number of alternative business models will be developed and explored. It is premature to predict which of these will succeed at this stage.

V. Conclusions and Directions for Future Research

This article presents preliminary thoughts on the nature of IP bandwidth markets, their likely antecedents, the reasons why these markets are needed, and a discussion of some of the challenges to the emergence of these markets. This discussion admittedly suggests more questions than answers. In this section, we identify several of the areas where additional research is needed and possible strategies for undertaking this research.

While the exact form these markets will take, the path by which they will emerge, and their mode of operation is uncertain at this time, the emergence of viable IP bandwidth markets is essential to the continued evolution of a healthily heterogeneous Internet. Moreover, from a public policy perspective, these markets are desirable because they would help sustain wholesale competition among competing facilities and non-facilities based carriers. Such competition promotes innovation and allows more flexible use of existing and future infrastructure. Therefore, a better understanding of the challenges and issues associated with the emergence of bandwidth markets is needed.

Additional academic and industry research into bandwidth markets must address the following questions and issues.

- Theoretical economic models

Additional theoretical work on the economics of competition in network industries is needed. We need to understand whether competition among wholesale vendors of a commodity service is sustainable when most of the costs are sunkn or fixed (*i.e.*, how to address the threat of destructive Bertrand price competition?).

In addition to better models of network competition, we also need economic and analysis of the issues that must be addressed approaches if bandwidth markets are to emerge. Are there antitrust concerns that need to be addressed? What sorts of institutions may emerge? Will they be national or supra-national organizations? What is the economic purpose/function of bandwidth markets? Will they facilitate the design and building of less costly infrastructure?

In addition to real-time bandwidth markets, there may also be secondary markets for capacity that would allow more fluid exchange of capacity. A better understanding of how these markets would operate and the role they would play would be useful.

- Capacity forecasts

For bandwidth markets to be feasible, suppliers must have excess capacity. The existence of excess capacity among any particular supplier is not inconsistent with the absence of industry excess capacity. Even if surplus capacity is localized, markets may serve to match supply and demand. On the other hand, the presence of generic excess capacity makes these markets even more likely. Therefore, it would be useful to be better informed regarding current capacity plans at various levels of market aggregation and the conditions under which these would be excessive or sufficient to meet market demand. This would include refined traffic models that enable us to better understand how multimedia traffic will evolve and behave over time.

- Technical characterization of bandwidth markets

We need better insight into the technical characteristics of how these markets would operate. What would buyers buy and sellers sell? Would it be IP transport between two specified nodes or would it be general termination capability among a collection of end nodes. Would it be bi-directional? Would it be time dated? How would it be implemented? We need several clear descriptions of specific types of bandwidth markets.

- Case studies from other wholesale data/telecom transport markets

Today, there already exist wholesale markets for a number of telecommunication and data communication services. These include:

  - Frame relay
  - ATM
  - Leased lines
  - Satellite transponders
  - Undersea cable RTUs
  - Current Internet bandwidth exchanges such as BandX, ITXC, and Digital Island.

Case studies of these markets and their relationships and potential for evolving into next-generation IP bandwidth market ought to be explored. In addition, it is worth considering examples from other industries. These might include:

  - Intermodal transport capacity (e.g., freight, airline seats)
  - Financial markets for stocks, bonds, and commodities
  - Electric power wheeling arrangements

Characterization of how these markets emerged and how they are structured may provide useful insight into how bandwidth markets may evolve.

- Industry Strategic/Scenario Analysis

We have argued that the emergence of bandwidth markets is necessary to facilitate less-integrated industry strategies, as explained in Section III. The form these markets will take if they do develop as we expect, will have profound implications for future industry structure. Models that explore and contrast the impact of alternative forms for these markets would provide useful insight into which forms are most likely to succeed and which may yield the greatest benefits in terms of encouraging competition and promoting the development of our global information infrastructure. Comparison of alternative scenarios and frameworks will help us conceptualize the issues that need to be addressed and which were partially enumerated in Section IV above.

- Design and implementation of automated auction or trading mechanisms for bandwidth markets.

We need additional research on the mathematics and performance characteristics of alternative bandwidth trading or auction mechanisms. We need to explore prototype versions of such markets and consider more carefully the costs and benefits of alternative designs for these mechanisms. This includes a wide agenda of technical work developing hardware and software interfaces, equipment, and programs to support different market mechanisms. In addition to evaluating alternatives on the basis of their technical merits, it will be useful to consider the economic and policy implications of different solutions. This will require multidisciplinary collaboration.

The above discussion provides a partial listing of the types of research projects that are on-going or ought to be on-going in both academic and industry. We expect that this research agenda will expand and deepen over the next few years as the need for and the potential for IP bandwidth markets becomes more generally recognized.

- National, International, and Self-Regulatory Policy Mechanisms for Bandwidth Markets.

As we noted above, some level of government oversight is inevitable, if bandwidth markets grow in size and significance as we expect. However, it is premature to determine the appropriate balance between market forces, self-regulation, national and international policy instruments. Additional research into policy options is important, but it is also important that policy-makers not attempt to intervene before the technologies and markets have a chance to develop. With bandwidth markets, we are entering an important experimentation phase from which we all hope to learn important lessons.